

Core-shift and precession in the jet of LS I +61°303

M. Massi

Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, D-53121 Bonn, Germany

E. Ros

Departament d'Astronomia i Astrofísica, Univ. de València, E-46100 Burjassot, Valencia, Spain and

Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, D-53121 Bonn, Germany

L. Zimmermann

Max Planck Institut für Radioastronomie, Auf dem Hügel 69, D-53121 Bonn, Germany

LS I +61°303 is one of the few GeV- and TeV-emitting X-ray binaries with a prominent, well-studied modulated radio and gamma-ray emission. Changes in its radio morphology suggested in the past the hypothesis of a precessing microquasar. In 2006, a set of VLBA observations performed all around the orbit and confirming the fast variation in morphology were not used to study the precession because the source was explained in the context of the pulsar model, the alternative model for this system. However, a recent radio spectral index analysis over 6.7 years from Green Bank Interferometer data at 2.2 GHz and 8.3 GHz has well confirmed the predictions of the microquasar scenario in LS I +61°303. At the light of these results we reanalysed the set of VLBA observations that constitutes a unique tool to determine the precession period and render a better understanding of the physical mechanism behind the precession. We improved the dynamic range of the images by a factor of four using self-calibration, and the self-calibrated maps reveal, in six out of ten images, a double-sided structure. The double-sided structure has variable position angle and switches at some epochs to a one-sided structure. These variations indicate a scenario where the precessing jet, inducing variable Doppler boosting, points close to our line of sight - a microblazar, the galactic version of the extra-galactic blazars. High energy observations of LS I +61°303 are consistent with the microblazar nature of this object. Moreover, we suggest in LS I +61°303 the first case of core shift effect observed in a microquasar. Because of this effect, well known in AGN, the cm-core of the jet is rather displaced from the system center. In LS I +61°303, the cm-core of the jet traces a large ellipse, 7 times larger than the orbit, in a period of about 28 d. Our hypothesis is that this ellipse is the cross-section of the precession cone of the jet at the distance of the 3.6 cm-core, and its period is the precession period.

1. Introduction

LS I +61°303 is a high-mass X-ray binary (HMXB) where the compact object travels through the dense equatorial wind of a rapidly rotating B0 Ve star. The nature of the compact object is still unknown due to its large mass range, $1.4 M_{\odot} < M < 3.8 M_{\odot}$, which implies either a neutron star or a black hole.

Two models have been proposed for this special HMXB, a strong and variable source at all wavelengths of the electromagnetic spectrum, from radio to TeV. One model assumes that the compact object is a non-accreting young pulsar whose relativistic wind strongly interacts with the wind of the Be star. The second model instead proposes a microquasar, that is, an accreting object whose steady jet, perpendicular to the accretion disk, is occasionally travelled by shocks associated to transients. The peculiarity of LS I +61°303 is that, due to the eccentricity of the system, two episodes of a large mass accretion rate may occur along the orbit and consequently two transients may occur per orbital period (26.496 d) (see references in [1]).

In 1993, VLBI observations of LS I +61°303 showed that the radio emission had a structure of milliarc-second (mas) size corresponding to a few AU at the distance of 2.0 kpc [2]. However, the complex morphology in successive VLBI observations [3, 4, 5, 6, 7] made an interpretation in terms of a collimated ejection

with a constant position angle difficult. The radio morphology not only changes position angle, but sometimes it is even one-sided while at other times two-sided. This fact suggested the hypothesis of LS I +61°303 being a precessing microblazar [4].

A microblazar should be the galactic version of the extragalactic blazars, i.e., AGN with radio jets forming a small angle, θ , with respect to the observer's line of sight. Doppler boosting enhances the radiation from material that is moving towards the observer, and attenuates it, if it moves in the opposite direction. For remarkable flux attenuation of the receding jet (i.e., attenuated to a level under the sensitivity of radio images) the structure will appear as a one-sided jet. A precession of the jet implies a variation of the angle and therefore variable Doppler boosting. The result is both, a continuous variation of the position angle of the radio emitting structure and of the flux density ratio between approaching and receding jet [8].

In known precessing X-ray binaries, the timescale for tidally forced precession of the accretion disk around the compact object, induced by the companion star, lies within the range 8 – 22 times the orbital period [9, 10]. In this context, the peculiarity of the variations of LS I +61°303 is their short timescale with respect to the predicted $(8-22) \times 26.496$ d. In fact, MERLIN images revealed a surprising variation of 60° in position angle in only one day [4]. Even if quanti-

tatively the relationship between position angle in the image and the viewing angle θ is not straightforward, a fast variation in position angle implies nevertheless clearly a fast variation in θ . The fast position angle variation measured with MERLIN was confirmed by VLBA observations [11] measuring in VLBA images a rotation of the inner structure of roughly 5° – 7° in 2.5 hrs, that is again almost 60° /day. In that work some one-sided structures were taken as evidence for the cometary tail of the pulsar model. If the compact object is a pulsar, the interaction between its relativistic wind and the equatorial wind of the Be star is predicted to create a bow-shock around the pulsar with a sort of cometary tail, i.e., a one-sided structure, extending away from the Be star [12].

However, recent analysis of the radio spectral index over 6.7 years from Green Bank Interferometer data at 2.2 GHz and 8.3 GHz discovered new characteristics in the radio emission of LS I +61°303 [1]. This analysis has proven that in LS I +61°303 occurs the typical characteristic of microquasars of an optically thin outburst after an interval of optically thick emission. In microquasars, the so called transient jet, associated to the large optically thin outburst, is related to shocks travelling in a pre-existing steady jet, that is a slow moving continuous conical outflow with a composite flat/inverted radio spectrum (i.e., optically thick emission) [13, 35]. The remarkable fact in LS I +61°303 is that, during the maximum of the long-term radio periodicity (4.6 yr) present in this source, the alternance, optically thick/thin emission, occurs twice along the orbit, first around periastron and then again, shifted almost 0.3–0.4 in orbital phase towards apastron (i.e., $(0.3-0.4) \times 26.496 \text{ d} = (8-11) \text{ d}$ after periastron) [1]. This agrees qualitatively and quantitatively with the well known “two peak accretion/ejection model”, applied by several authors in LS I +61°303, predicting for large mass accretion rate, \dot{M} , two events: one event around periastron and the second one shifted about 0.3 in orbital phase towards apastron [15, 16, 17, 18].

As a matter of fact, the radio spectral index data corroborate the microquasar model for LS I +61°303. Then, the open issue is what would produce the observed fast precession. The basis for such a study is to establish the precessional period. This important parameter could be derived by the re-analysis of the VLBA observations performed every 3 days over 30 consecutive days, towards the minimum of the long-term radio periodicity [11]. We present here preliminary results of our analysis [19].

2. Results

2.1. Images: the fast changing structure from a double-sided morphology to a one-sided morphology

The 8.4 GHz phase-referenced images (with respect to J0244+6228) shown in Fig. 1-Top, well reproduce the structures in [11]. At their center, we show the orbit with semimajor axis of $(0.22 - 0.23) \text{ mas}$ ($\simeq 0.7 \times 10^{13} \text{ cm}$ at a distance of 2 kpc), derived from Kepler’s 3rd law for $P = 26.496 \pm 0.008 \text{ d}$ with a mass for the B0 star of $17 M_\odot$ and a mass of the compact object of $1.4 M_\odot - 4 M_\odot$, and traced using the orbital parameters from [20]. The orbit is not only much smaller than the radio emitting region, but also less than the interferometric beam of the VLBA at this wavelength. We remark this, because the zoomed orbit in Fig. 3 of [11] (zoomed to better show the orbital phase of each run) may unfortunately produce the wrong impression that the orbit is resolved whereas it is not.

For each run are presented, in Fig. 1, along with the phase-referenced ones also the self-calibrated images with natural and uniform weights respectively. The self-calibrated images were produced with the automatic procedure Muppet of the Caltech Difmap imaging package [21]. Using self-calibration, the information on absolute flux density and absolute position are lost, but the removal of residual calibration errors improves the dynamic range up to a factor of 4 for our maps. The higher dynamic range of the self-calibrated maps show in the image of run A a double component structure. The double structure in run A is clearly unlikely for a pulsar nebula, whereas it could be compatible with either the approaching and receding component of a transient jet, or with variable Doppler boosting along a one-sided twisted jet. Image B shows already in the phase referenced map with natural weighting a double-sided morphology difficult to conciliate with the pulsar nebula. The self-calibrated map shows an intriguing twisted jet as expected for a fast precession. Runs C, F, I, and J show a one-sided jet or alternatively a pulsar cometary-tail but again runs D, E, G, and H show the double-sided jet structure.

2.2. Astrometry: all points form one ellipse

The peak position in the phase-referenced maps are plotted in Fig. 2-Bottom. It is evident that the peaks trace well an ellipse 6–7 times larger than the orbit. Our hypothesis is that this ellipse is the cross-section of the precession cone, at the distance of the 3.6 cm-core ($\nu = 8.4 \text{ GHz}$) of the steady jet.

In fact, changes in the electron energy distribution and the decay of the magnetic field along the con-

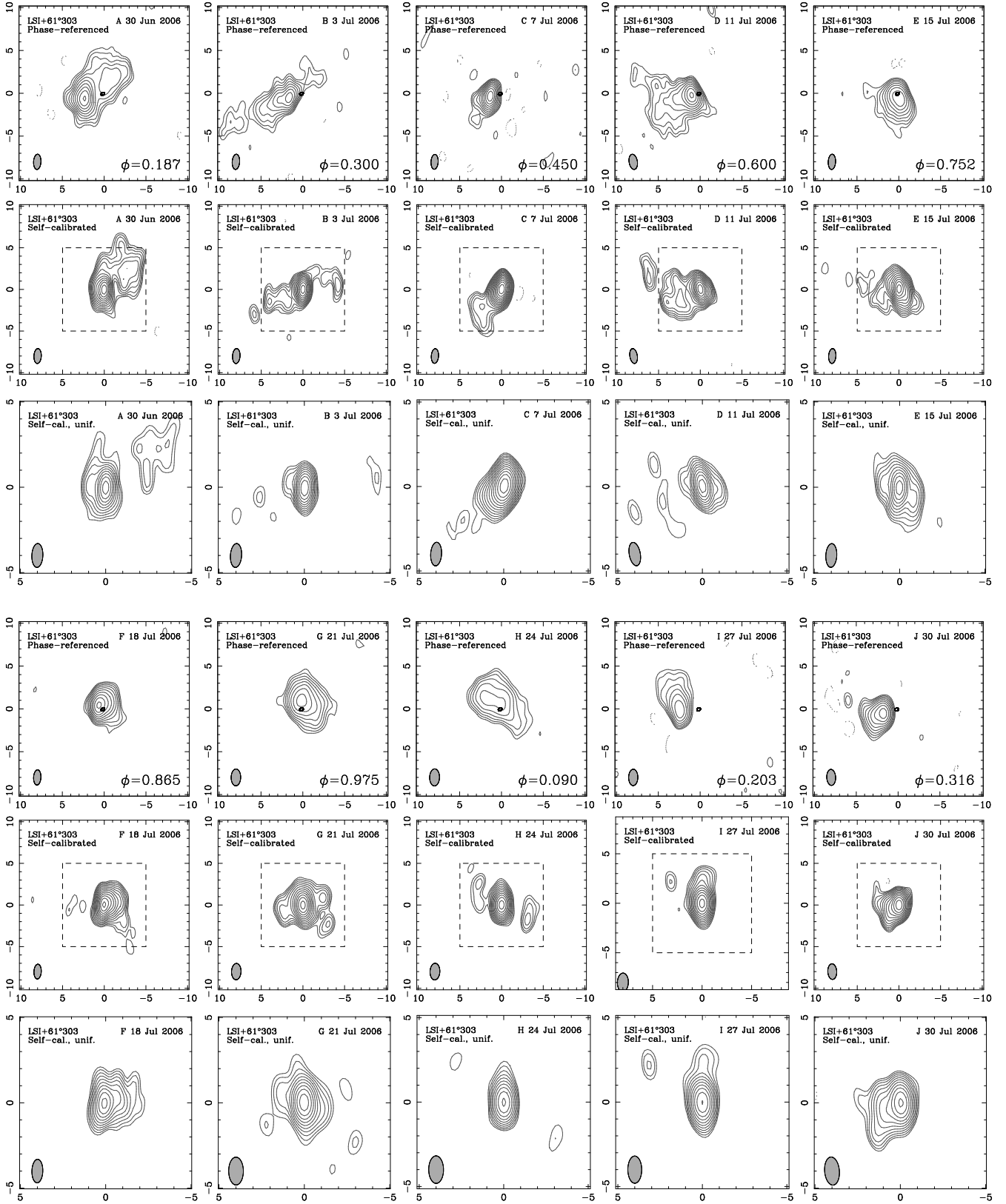


Figure 1: Images of VLBA runs A-J at 8.4 GHz (3.6 cm) of LSI I +61°303 [19]. The units on the axes are milliarcseconds (mas). For each run three maps are presented, the phase-referenced map (beam of (1.8–2.0) mas \times (0.9–1.1) mas, shown in the bottom left corner), the self-calibrated map at the same resolution and the self-calibrated map with a beam of (1.4–1.6 mas \times (0.6–0.9) mas. Contour levels for all maps are $-4, 4, 5.66, 8, 11.3, 16, 22.6, 32, 45.2, 64, 90.5, 128, 181 \sigma$ (with $1\sigma = 0.1$ mJy/beam for Top and Bottom maps, $1\sigma \simeq 0.07$ mJy/beam for Middle maps). At the center of the phase-referenced images is traced, in scale, the orbit (see Sect. 2).

ical outflow forming the steady jet, imply that the critical frequency, ν_{break} , of the synchrotron spectrum varies along the jet [22, 35]. In microquasars, the ν_{break} for the part of the steady jet closest to the engine (i.e., ν_{break_1} in Fig. 2) lies in the infrared [23], whereas in AGN the observed turnover lies in the millimeter range [22]. Observing at longer wavelengths than infrared, i.e., in the radio band, gives rise to two results: a flat spectrum and the “core shift”. Multi-wavelength observations result in fact in the flat/inverted spectrum discussed in the introduction, typical for a steady jet. Imaging a steady jet at one observing frequency ν_{obs} , gives rise to the effect known as “core shift” [25], with the displacement from the center as a function of the observing frequency ν_{obs} . At ν_{obs} the emission of the segment will dominate, whose spectrum peaks at that frequency plus small contributions from neighboring segments (see Fig. 1 in [24]). With the engine being close to the “infrared-core”, it is clear that the 3.6 cm-core can be rather displaced from the center (like segment 2 is displaced with respect to the center in Fig. 2 Top-Left) [22, 25, 35]. If a jet is pointing towards us (i.e., a microblazar as in Fig. 2 Top-Right) the core will be dominated by the approaching jet, because of Doppler boosting. If the jet is precessing, then the core will describe an ellipse (see both ellipses, the observed ellipse in Fig. 2-Bottom and the predicted ellipse for the blueshifted segment-2 in Fig. 2 Top-Right). A transient jet, on the contrary, can have any shift from the center, depending on the velocity and the time elapsed from the transient. The peak of map E, even if displaced from the other ones, and therefore likely affected by the approaching component of the transient jet, is at a position angle which is consistent with the other peaks.

Note as after 27 d, the peak of run I is rather close to completing the cycle, i.e. to overlap with the peak of the starting run A. The same occurs for peak of run J, that 27 d after run B, nearly overlaps with peak B. The peak of run J, 30 d after run A, is clearly rather displaced from the A peak. The period seems therefore to be in the range (27–28) d.

3. Conclusions and Discussion

LS I +61°303 is one of the few established massive X-ray binaries that emit in the high and very high energy range. It is formed by a compact object of unknown nature (black hole or neutron star) travelling with a period of 26.496 d around a Be star. Two models have been proposed in the past: a millisecond pulsar and a microquasar model. Recent analysis of the radio spectral index has proven in LS I +61°303 the typical characteristic of microquasars of an optically thin outburst after an interval of optically thick emission twice along the orbit, as predicted by the two

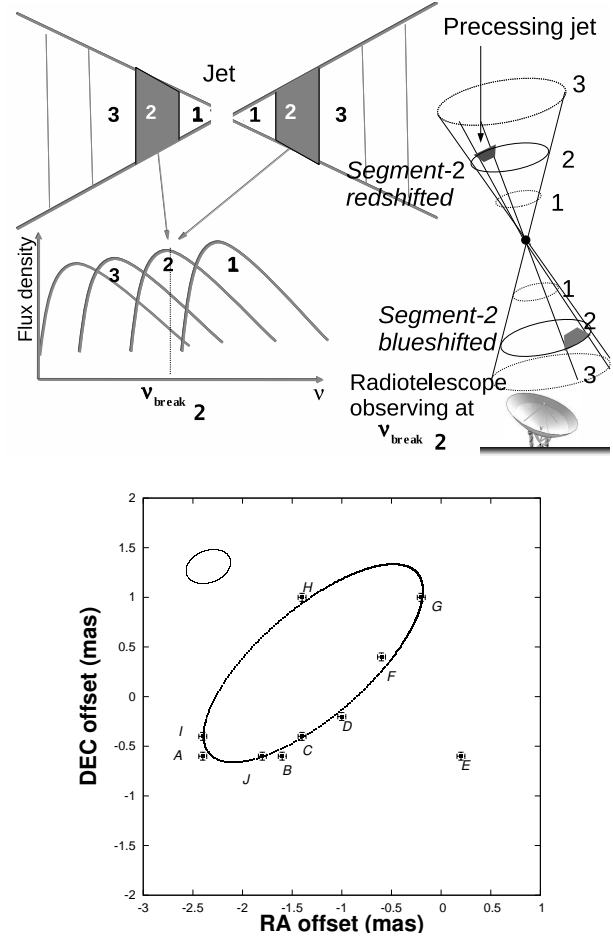


Figure 2: Top-Left: Superposition of individual spectra, each with a different break frequency associated with different segments of a steady jet. Top-Right: For a precessing microblazar, i.e., for small angle of ejection with respect to the line of sight, the core component, dominated by the approaching jet contribution because of Doppler boosting, will describe an ellipse during precession. Bottom: Astrometry of consecutive peaks of VLBA 8.4 GHz maps for runs A-J with the orbit drawn in scale at an arbitrary distance. The quality of the astrometry is determined from the scatter in positions of the check source J0239+6005 [19]. The peak of map E, even if displaced from the other ones, and therefore likely affected by the approaching component of the transient jet, is at a position angle which is consistent with the other peaks. The fact that the precessing compact object is moving in an orbit with semimajor axis of ~ 0.2 mas introduces additional variations [19].

peak microquasar model.

The results of our re-analysis of VLBA observations of LS I +61°303 presented here are that the radio emission has in several images a double-sided structure (see. Fig. 1). The astrometry show that the peaks of the images trace a well defined ellipse in (27–28) d (see Fig. 2). The pulsar model explains neither the double-sided morphology nor the observed

change from double sided to a one-sided structure. The microquasar model can explain them with variable Doppler boosting, i.e., with a precessing jet. The cm-core of a precessing steady jet pointing close to our line of sight, as in a microblazar, is expected to describe an ellipse during the precession. During the transient jet phase there will be an additional shift due to the approaching jet component. We conclude therefore that the precession period is the time of (27–28) d necessary to complete the ellipse.

A precession period of (27–28) d for the accretion disk in LS I +61°303 induced by tidal forces of the Be star [10] would require the unrealistic value for the size of the accretion disk of $0.5 - 0.8 \times 10^{13}$ cm, i.e., nearly the semi-major axis, and can therefore be ruled out. On the contrary, for a slow rotating compact object, a precession period of 28 d induced by Lense-Thirring effect (i.e., frame dragging produced by the rotation of the compact object) could be compatible [10].

High energy observations of LS I +61°303 are consistent with the microblazar nature of this object. Simultaneous X-ray and VHE observations during an outburst of LS I +61°303 resulted in a correlation, indicating a simultaneity in the emission processes [26]. In particular, with respect to the comparison with blazars, it has been noticed [10] as the two fluxes result in $F_{\text{VHE}} \propto F_{\text{X}}^{\eta}$ with $\eta = 0.99$ in agreement with the correlation observed in blazars [27]. In addition, the respective values of the photon indices seem to be comparable. During a bright flaring event of the blazar 1ES 2344+514, VERITAS measured a photon index of $\Gamma = 2.43 \pm 0.22$, whereas for the X-ray emission, RXTE and Swift-XRT measured a hard photon index of ~ 1.9 [28]. For LS I +61°303: MAGIC had a $\Gamma = 2.7$ and the X-ray emission detected by *XMM-Newton* and Swift-XRT a harder photon index of 1.5-1.8 [26]. In blazars the X-ray emission is due to synchrotron, and VHE is synchrotron self-Compton (SSC) [29]. As discussed in [30], several authors have in fact explained the X-ray excess around apastron in LS I +61°303 with synchrotron and the VHE with either external inverse Compton (EIC) or SSC emission [31, 32]. In particular, the X-ray/VHE correlation in LS I +61°303 [26] is compatible with a one zone leptonic particle population producing the emission [26, 32]. Concerning high energy emission in the GeV range, detected e.g., with *Fermi*-LAT, GeV emission is seen all along the orbit. In fact, electrons from the steady jet can always upscatter stellar UV photons to GeV energies (i.e., EIC see [15]). Nevertheless, more energetic particles from the transient jet could in addition also produce GeV emission via EIC and SSC. Intriguingly, the spectrum measured by *Fermi*-LAT shows, in addition to a power law with a cut-off around 6 GeV, upper limits possibly compatible with the spectrum measured with MAGIC and VERITAS (see e.g., Figs. 2 and 3 in [33] and discussion in [30]). As a matter of fact, there is an interesting increase in

the overall flux level observed with *Fermi*-LAT after March 2009 together with a broadening of the peak shape [33]. The up to now observed *Fermi*-LAT variations are therefore consistent with a long term variation. Similarly, strong variations are observed at very high energies. With VERITAS the source went from being detected around apastron to becoming quiescent between 2008 and 2010 [34]. With respect to the long-term, 4.6 yr, radio periodicity mentioned in Sect. 1, the insufficient temporal coverage at high energy, evident in Fig. 1 of [30], does not allow at the moment a more closer comparison. However, a different trend with respect to the 4.6 yr radio periodicity is expected. In fact, the high energy emission is indeed related to the steady jet but its peak seems to occur during the transient jet and not during the steady one (Fig. 4 in [35]). As a matter of fact the steady jet, related to the radio periodicity, is not always followed by the transient one. A timing analysis of the transient jet is in progress.

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